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Electricity Storage
Handbook

In Collaboration
with NRECA

ESHB[3RG]

Ready Reference Resource Guide

Ready Resource Reference
Guide Organized by
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ESHB 3RG

Table of Contents

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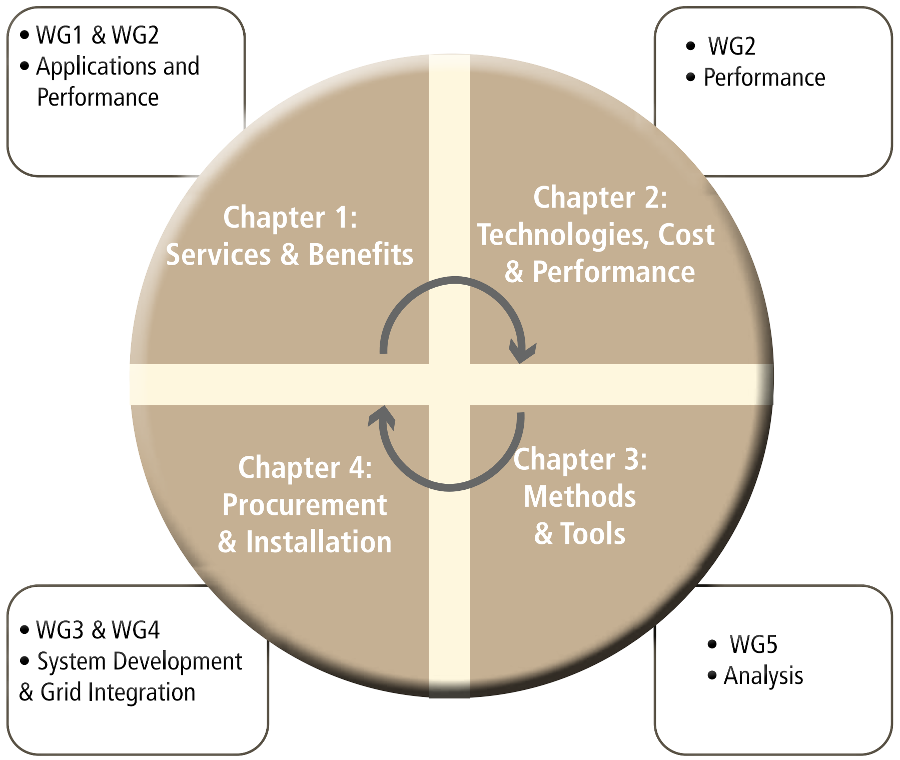
The design rationale: I was fascinated by the idea of a very old 'energy storage system' ... a simple spring. The cover depicts a spring in half kinetic / half potential state. Screened down, so as barely visible, are actual springs and spring formula embedded throughout the book. Additionally, the cover is the color of a blackboard - as I wanted to address an 'academic' audience - that color seemed fitting.

The authors thank the U.S. Department of Energy's Office of Electricity and Dr. Imre Gyuk, Energy Storage Program, Manager, Haresh Kamath of the Electric Power Research Institute, Robbin Christianson of the National Rural Electric Cooperative Association, and the Energy Storage Handbook Advisory Panel and other contributors for the collaborative efforts through all phases in the development and compilation of the Electricity Storage Handbook (ESHB).

Introduction

The unabridged DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA is a 340-page How-to Guide. Many refer to this SAND Report document by the acronym ESHB. The figure below is a working model from A. Akhil to illustrate the higher-level view of the collaboration.



The most current version of the ESHB is composed of four chapters, with well over one hundred figures and twenty tables in the main body, seven comprehensive appendices, and an extensive glossary. The handbook engaged the talent of nine primary authors from four separate organizations, an advisory panel of ten subject matter experts, a construct of five different working groups, and another varied host of contributors.

The purpose of the ESHB is to serve as a resource for making decisions on technical devices, equipment, facilities, systems, and installations based on respective use cases, services, costs and benefits for the emerging technologies and applications associated with electrical energy storage. Stakeholders who require this type of information include, but are not limited to, large electricity utility and rural cooperative engineers, investors, venture capitalists, resource planners, and end-users.

This Ready Reference Resource Guide (3RG) is a clearinghouse catalogue that is concise, with practical information and advice on the major topics included in the full resource. It is a challenging task to decide what should be included in this brief, magazine style layout. However, the benefits of this short digest are important: simplicity of communication, document usability, more exposure to targeted audiences, solution for handouts, and material that has a greater likelihood of being read and reviewed. Lastly, this guide also points to the major topics for the next iteration of the ESHB.

Chapter 1. ELECTRICITY STORAGE SERVICES AND BENEFITS

Operational changes to the grid, caused by restructuring of the electric utility industry and electricity storage technology advancements, have created an opportunity for storage systems to provide expanded unique services to the evolving grid. This Handbook combines the knowledge base of reports including: Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide, which expanded the range of the grid services; provided significant detail on 17 services; and provided guidance on estimating the benefits accrued by these services, and EPRI's Smart Grid Resource Center Use Case Repository, which contains over 130 documents that discuss various aspects of storage and includes the description and service-specific technical detail of 18 services and applications in five umbrella groups, as listed below.

Bulk Energy Services
- Electric Energy Time-Shift (Arbitrage)
- Electric Supply Capacity

Ancillary Services
- Regulation
- Spinning, Non-Spinning and Supplemental Reserves
- Voltage Support
- Black Start
- Other Related Uses

Transmission Infrastructure Services
- Transmission Upgrade Deferral
- Transmission Congestion Relief

Distribution Infrastructure Services
- Distribution
- Upgrade Deferral
- Voltage Support

Customer Energy Management Services
- Power Quality
- Power Reliability
- Retail Electric Energy Time-Shift
- Demand Charge Management

The Handbook and its appendices provide many graphs and illustrations demonstrating the various benefits and details of energy storage systems.

One of the Ancillary Services, Black Start, which provides an active reserve of power and energy within the grid can be used to energize transmission and distribution lines and provide station power to bring power plants on line after a catastrophic failure of the grid.

The operation of the battery is illustrated in the graphical description below. Figure 8 shows its discharge to provide charging current to two transmission paths as needed, as well as start-up power to two diesel power plants.

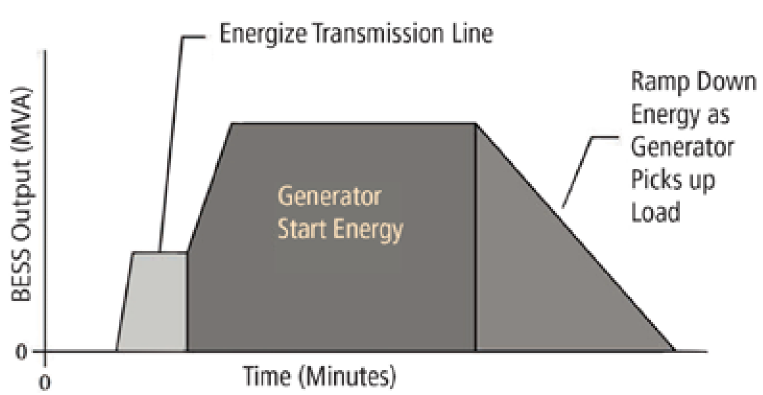


Figure 8. Black Start Service by Storage

(Courtesy: Golden Valley Electric Association)

SERVICES AND BENEFITS

Service	System Size	Target Discharge/ Duration	Minimum Cycles/Yr	Function	Characteristics	Benefit
Bulk Energy Services						
Arbitrage	1-500 MW	< 1 Hour	250+	Time-shifting	Variable operating cost affects round-trip efficiency	Support PV and Wind generation
Supply Capacity	1-500 MW	2-6 Hours	5-100	Defer central station generation	Location-specific	Flexible duration; market mechanism
Ancillary Services						
Regulation	10-40 MW	15 min- 1Hr	250-10,000	Regulation	Rapid response; fast ramp rate	Access to and response to either ACE or AGC signal
Spinning Reserve (Synchronized) Non-Spinning & Supplemental Reserve	10-100 MW	15 min- 1Hr	20-50	Spinning Reserve can be used for generation shortfall	ES for reserve capacity does not discharge at all; services used for transmission outage	Maintain frequency for the grid; discharge only when needed
Voltage Support	1-10 MVAR	N/A	N/A	Offsets reactive effects	Enables transmission system stability	Can allow multiple VAR support resources near large loads
Black Start	5-50 MW	15 min- 1Hr	10-20	Provides power after a system failure	Useful in the case of a catastrophic event	ES can provide charging current and start-up power
Load Following	1-1000 MW	15 min – 1Hr	N/A	Can be used to firm renewable resources, time-shifting, reserve capacity	Requires access to ISO's AGC	Used to meet contractual market bidding obligations
Transmission Infrastructure						
Upgrade Deferral	10-100 MW	2-8 Hours	10-50	Delays necessity to upgrade system	Reduces Immediate Cost	External equipment life extended (i.e., transformers, underground cables
Congestion Relief	1-100MW	1-4 Hours	50-100	Discharges during congestion	Reduces and/or eliminates congestion-related costs	May only require a few hours of support per year
Transmission Stability Damping; Sub-Synch. Resonance Damping	10-100MW	5 sec – 2Hr	20-100	Increase dynamic stability	Can provide real and/or reactive power modulation at sub-synchronous frequencies	Allows for higher levels of series compensation
Distribution Infrastructure Services						
Upgrade Deferral	500kW-10MW	1-4 Hours	50-100	Delays upgrade investment; allows for replacement of stressed components	Delays cost; extends the system's operational life by years	ES can provide distribution benefits with limited or no need to discharge
Voltage Support	500kW-10MW	1-4 Hours	50-100	Delays upgrade investment; allows for replacement of stressed components	Delays cost; extends the system's operational life by years	ES can provide distribution benefits with limited or no need to discharge
Customer Energy Management Services						
Power Quality [Power Reliability]	100kW-10MW	10 sec-15 min	10-200	Monitors quality and discharges to smooth disturbances	Protects customers from future quality	Protects sensitive processes and loads at the customer's site; Can be treated as demand-side charge for either customer or electric utility
Retail Energy Time-Shift	1kW-1MW	1-6 Hours	50-250	Charge during off-peak, discharge on-peak when costs are elevated	End users reduce their overall electricity costs	Time of Use (TOU) options available for prevailing wholesale price
Demand Charge Management	50kW-10MW	1-4 Hours	50-500	Reduction of demand during peak periods specified by utility	End user reduces overall costs by reducing demand during peak periods	Demand charge offset available for customer

Chapter 2. ELECTRICITY STORAGE TECHNOLOGIES: COST, PERFORMANCE, AND MATURITY

Introduction

Chapter 2 presents a review of the currently available and emerging electricity storage technologies that are anticipated to be available within the next two to three years. The handbook provides a snapshot of the status, trends in deployment, data sheets on performance, and design features. Estimates of life-cycle costs for each technology are also provided, along with the key assumptions. More detailed cost breakdowns for each technology and the cost metrics are provided in Appendix B.

Storage Technologies Overview

The portfolio of electricity storage technologies can be considered for providing a range of services to the electric grid and can be positioned around their power and energy relationship. This relationship is illustrated on page 7, which shows that compressed air energy storage (CAES) and pumped hydro are capable of discharge times in tens of hours, with correspondingly high sizes that reach 1000 MW. In contrast to the capabilities of these two technologies, various electrochemical batteries and flywheels are positioned around lower power and shorter discharge times.

Traditionally, economies of scale have dictated that pumped hydro be sized for storage times that exceed 8 to 10 hours – necessary to amortize the cost of large storage reservoirs, dams, and civil engineering work that are integral to this technology. Similarly, CAES requires developing large underground or large steel above-ground storage reservoirs to store the compressed air. In contrast to these large sizes, flywheels and the family of batteries cluster in the lower end of the discharge duration spectrum, ranging from a few seconds to 6 hours

Approach

More than 50 battery original equipment manufacturers (OEMs), power electronics system providers, and system integrators were surveyed and asked to provide performance, cost, and O&M data for energy systems they could offer for various uses of storage. Vendor responses to this survey provided the basis for the information in the data sheets provided. An iterative approach was used to review scope of supply, cost data, and operation and performance data. Given the lack of credible O&M data for some technologies, proxies were developed to estimate fixed, variable, and periodic battery replacement costs shown in affordably.

Certain energy storage technologies are still in the R&D stage, process and project contingencies costs were added to develop installed costs, given the uncertainty in those cases.

Installed cost estimates were developed for the specific services and are presented per kW of discharge capacity installed. For technology screening-level studies, these cost estimates are conceptual estimates that will differ from site-specific project estimates for several reasons:

Project estimates are more detailed and based on site-specific conditions and use cases. Individual companies' design bases may vary. Actual owner costs as well as site-specific costs in project estimates are generally higher. Site-specific requirements, such as transportation, labor, interconnection, and permitting, also have an impact.

A rating system is used to define an overall confidence level for data presented in technology screening studies. One rating approach is based on a technology's development status; the other is based on the level of effort expended in the design and cost estimate. The confidence levels of the estimates presented in this report reflect technology development statuses ranging from early demonstration trials to mature development, with a preliminary or simplified level of effort. The rating system indicates the level of effort involved in developing the design and cost estimate.

Storage Technology	Description	Benefits/Limitations
Pumped Hydro	Employs off-peak electricity to pump water from a reservoir to another reservoir at a higher elevation; Water is released from the upper reservoir to generate electricity	Has the highest capacity of the assessed technologies, because its size is only limited by the reservoir size; long lives (50-60 years)
Compressed Air Storage	Uses off-peak electricity to compress air and store it. When needed, the compressed air is heated, expanded, and directed through an expander or conventional turbine-generator to produce electricity.	One of only two commercial bulk storage systems available today; long life
Sodium Sulfur Batteries	Commercial technology with applications in grid support, wind power integration, and high-value grid services	Long Discharge period (up to 6 hours)
Sodium-nickel-chloride	High Temperature battery devices	
Vanadium Redox	These are flow batteries based on redox reactions of different ionic forms of vanadium	The two electrolytes are identical when fully discharged, making shipment and storage simple and inexpensive
Iron-Chromium	A Redox flow battery system using dissolved reactants	Simpler design and controls and lower cost; can be used for time-shift as well as frequency regulation services
Zinc-Bromine Batteries	A flow battery system	20 year life span; the active materials do not degrade, therefore the lifetime is less related to the number or cycles or depth of discharge and more dependent on the
Zinc-Air Batteries	Metal-air electrochemical cell technology	Only require one electrode and therefore can have very high energy densities; designs are relatively low cost.
Lead-Acid Batteries	Oldest form of rechargeable battery technology. Used in automotive, marine, telecommunications, and uninterpretable power supply systems	The environmental and safety hazards associated with lead require many regulations concerning the handling and disposal of lead-acid batteries
Flywheel Storage	Store energy in the form of the angular momentum of a spinning mass (rotor). The work done to spin the mass is stored in the form of kinetic energy which is then transferred into ac power through controls and power conversion systems	Flywheels can be charged relatively quickly, and possess few adverse environmental effects -- both in normal and in failure conditions. Very fast response time.
Family of Lithium-Ion Batteries	Fastest growing platform for stationary storage applications	Found in electric vehicles, notebook computers and portable power applications.

Chapter 3. METHODS AND TOOLS FOR EVALUATING ELECTRICITY STORAGE

Chapter 3 discusses screening-level and advanced production cost, electric stability, and financial tools that can be used to evaluate the impact of electricity storage in the grid.

A generalized approach for evaluating energy storage includes:

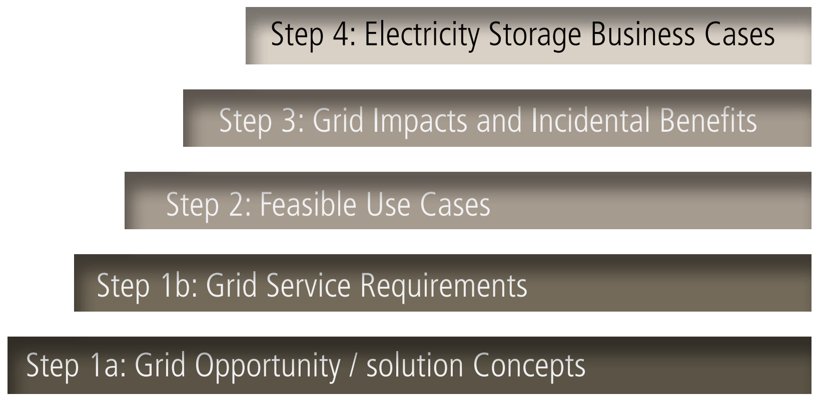
Assessing storage requirements and value originating from the locational needs of grid operators and planners;

Avoiding conflation or double-counting of benefits;

Drawing a distinction between quantifiable and monetizable services and direct and incidental benefits;

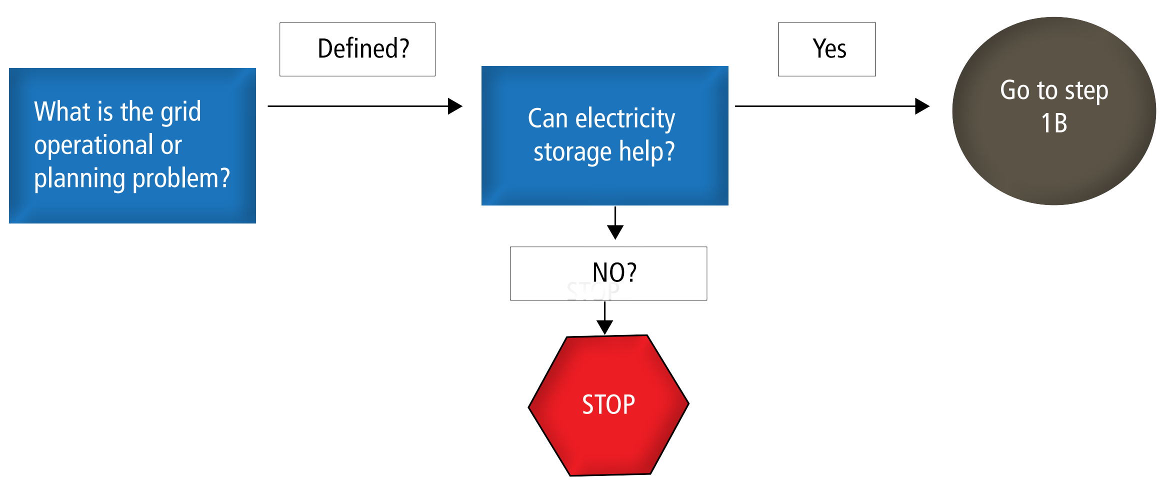
Delaying resource-intensive production simulation analyses until after technically feasible, cost-effective use cases are identified; and

Delaying deep investigation of policy and regulatory scenarios until after technically sound cost-effectiveness cases are identified and impacts modeled.

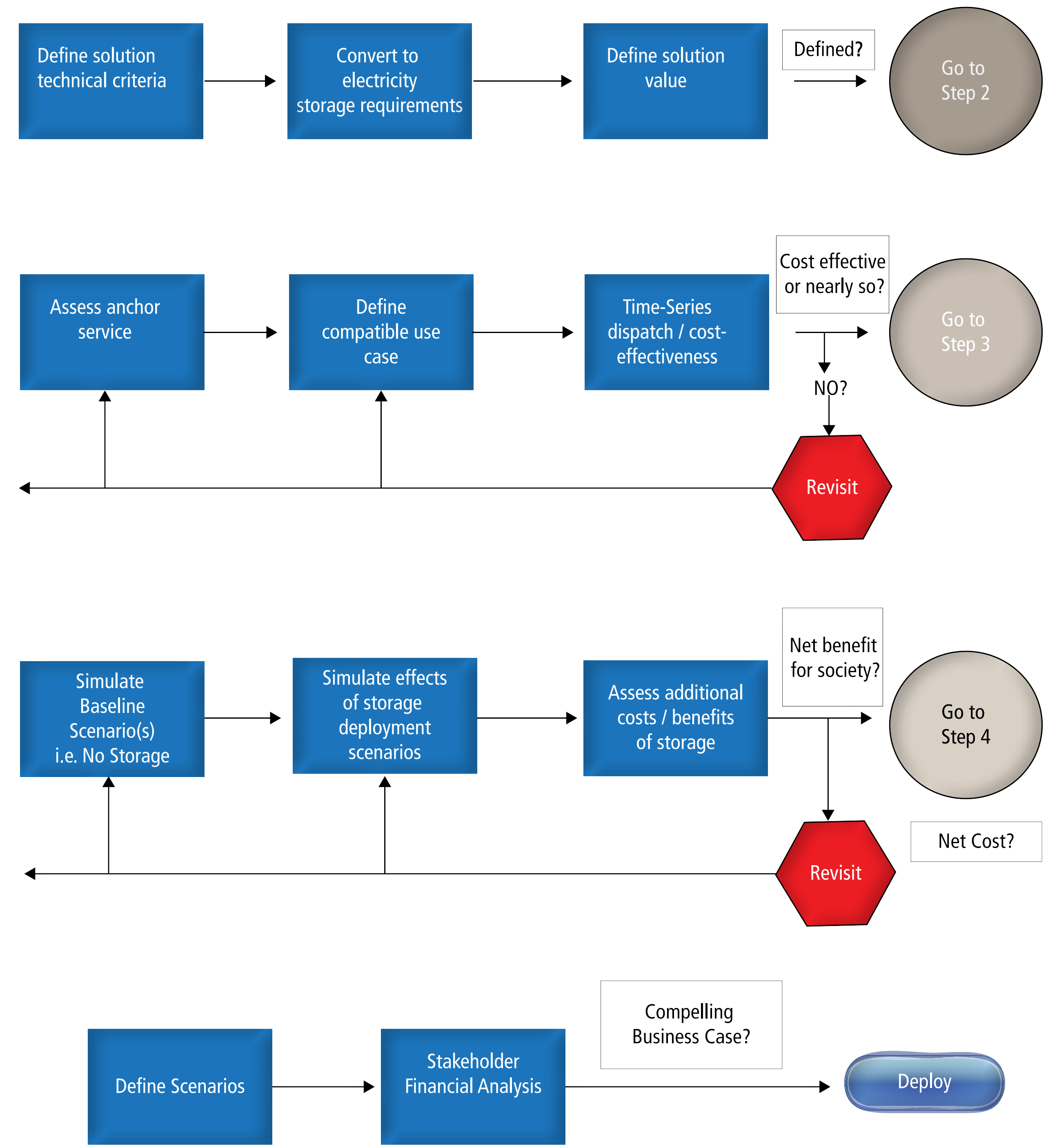


Steps in Electricity Storage Evaluation

Energy storage solves an existing problem for a utility, customer, investor, etc. The following five flow diagrams are illustrations of the practical steps necessary to make decisions about ES system size or needs. These tools are useful for developing a common approach to evaluate systems and technical specifications. Ultimately, following the proposed processes helps to make a strong business case for both the investor and the grid operator for the optimal use of energy storage.



Decision Diagram for Step 1a: Opportunity/Solution Concepts



Specific tools that support energy storage evaluations span the spectrum in the level of detail and complexity – from high-level screening to detailed analysis for site- and service-specific needs. Many of these tools have been identified and are listed in Table 18.

Chapter 4. STORAGE SYSTEMS PROCUREMENT AND INSTALLATION

Storage services for the grid can be acquired through several business models, as shown in Figure 122. These business models range from contracting for services only without owning the storage system to outright purchase. The specific option chosen depends on the varying needs and preferences of the owner. This chapter provides broad guidelines for acquiring electricity storage systems using different options.

Procurement Category	Characteristics	Details
Third Party Ownership	The storage system is owned, operated, and maintained by a third party who provides specific storage services according to a contractual arrangement.	Shelters the owners, utilities, and end users financially. Not widely adopted. Not preferable for those who prefer short payback and higher cash flows that outright sales generate.
Outright Purchase/ Full Ownership*	The current trend in storage system acquisitions has been toward obtaining the entire storage system on a turnkey basis. Turnkey acquisitions relieve the owning entity from specifying each subsystem individually and managing their procurement contracts and installation separately.	The two-step RFI/RFP procurement process provides a means for a non-binding exchange of information between the owners and vendors that allows them to assess each other's needs and capabilities.
Electric Co-op	Co-ops are split into two categories – distribution co-ops that deliver electricity to its consumers/owners and the generation and transmission (G&T) co-ops that are bulk power providers that own and operate generation assets or purchasing power on the market and sell to the distribution co-op. A key aspect of this relationship is that the G&T is owned by the distribution co-op it serves.	Distribution co-ops have an all-requirements contract with the G&T, meaning that special consideration must be made regarding which entity receives the benefits of an energy storage system. (For example, a G&T representing distribution co-ops in a regulated market would likely receive significant financial benefits from selling ancillary services like frequency regulation, whereas a distribution co-op likely would not.) On the other hand, a distribution co-op may find great value in reducing substation congestion, while a G&T likely does not, depending on the terms of the all-requirements contract. A G&T adds electricity storage for peak-shaving leading to load reduction, which will receive a capacity credit based upon avoided future cost, whereas distribution co-ops will receive a much higher reduction in the cost of their demand charges.

*The focus here is on battery and flywheel storage systems, because their procurement and installation lends itself to a more replicable process and is less project-specific.

Regulation

Energy storage systems and the services they provide can be sold in regulated and deregulated markets. However, almost all the electrical grid-connected storage services, market opportunities, cost-recovery methods, cost-effectiveness criteria, incentives, and rebates are governed by a well-established regulatory oversight and enforced by federal and state agencies. Consequently, these rules and regulations impact the growth of the storage industry, because policies can create or inhibit market opportunities for electricity storage and may determine how, and if, they will be compensated.

Safety

The electricity storage systems should have built-in safety features that are integrated into the overall system monitoring and performance architecture. Dedicated safety and environmental personnel with appropriate training and experience must be involved early in the project development phase to review and develop appropriate safety protocols, review procedures from a safety point of view, and provide guidance in environmental permitting.

Project Timelines

The larger size of pumped hydro and CAES storage facilities require much longer planning horizons due to the analysis and design activity that precedes their implementation. The relatively smaller battery or flywheel storage projects have been implemented within two to three years from conceptual inception to commissioning. Smaller storage systems in the 1-MW to 5- MW range have been commissioned in less than two years from initial conception to commissioning.

An overview of the typical timelines that can be expected for the procurement and installation of a storage technology are shown below in Figure 125.

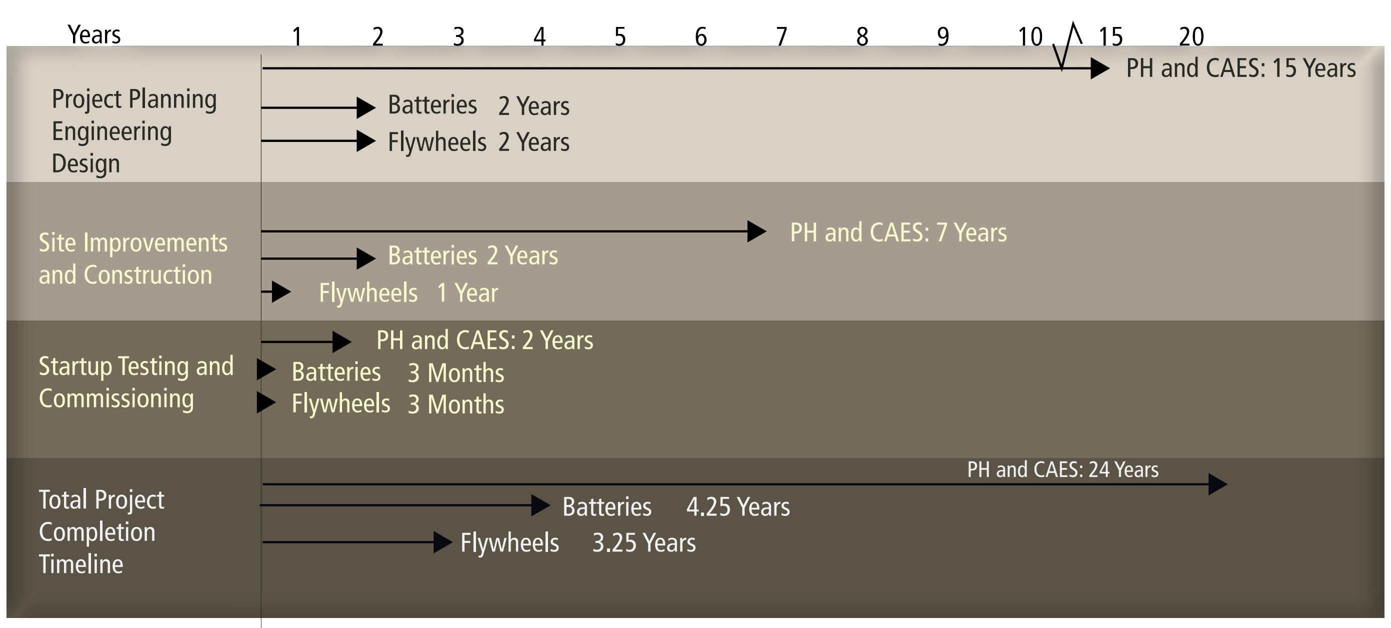


Figure 125. Typical Project Timelines

(PH) - Pumped Hydroelectric Energy Storage; (CAES) – Compressed Air Energy Storage

ESHB Appendices Summary

Appendix A: Review of Selected Tools

Tool	Capabilities
Technology Screening – ES Select™ Created by DNV GL KEMA in collaboration with Sandia Labs	Assesses feasibility for intended ES applications; designed to work with uncertainties of storage application characteristics, costs, benefits; decisions in the software program must be made based on what is known of the system; tool intended for higher level analysis
ES Valuation Tool Created by EPRI	Enables assessment of cost-effectiveness of different use cases; characteristics include site-customization, user-friendly, and transparent model and input; value of ES determined by using data from market, transmission, distribution, customer services; many outputs including value stream from (chosen) grid services
ES Computational Tool Created by Navigant Consulting in response to DOE/OE's request	Identifies, quantifies benefits accrued through services provided by ES; can be used to determine monetary value of ES deployment
Production Cost Simulation Models PLEXOS UPLAN- NMP	Objective of PC models is security-constrained economic dispatch of a system's generation units to meet load
Electric Power System Analysis Load Flow/ Stability PSS/E Positive Sequence Load Flow (PSFL)	Used for system planning; results include voltage and frequency stabilization; load flow problems solved using dynamic simulations; capable of evaluating large scale power systems

Appendix B: Storage System Cost Detail

Five Cost Metrics (with Units)	Important Elements for Calculating ES System Costs
Installed Cost ($/kW) Levelized Cost of Capacity ($/KW-yr) Levelized Cost of Energy (LCOE) (4/MWh) Present Value of Life-cycle Costs ($/kW Installed) Present Value of Life-cycle Costs ($/kWh Installed)	Life cycle cost analysis Financial Assumptions Accepted Methodology Annual Storage Costs

Appendix C: Sample Procurement Documents

Sample Documents in Appendix	Request for Information (RFI), Request for Proposal (RFP), Technical Specification for Procurement, Data Requirements for Acquisition

Appendix D: Utility and Owner Interconnection Costs and Schematics for Various Storage Systems

Appendix E: Regulations (that affect Energy Storage)

Non-Storage Regulatory Proceedings
Investment Recovery Requests
The Evolving Regulatory Environment for Energy Storage
Regulatory Database

Appendix F: Test Facilities (details)

DOE/SNL Energy Storage Test Pad and Energy Storage Evaluation Analysis Laboratory
Energy Storage Performance Test Laboratory
EPRI Knoxville Test Facility
Bonneville Power Authority Energy Storage Test Facility
NREL Energy Systems Integration Facility

Appendix G: Noteworthy Energy Storage Projects

Noteworthy Energy Storage Projects	Timeframe	ESHB Reference Page
Historical Electricity Storage Projects	1987-2003	PP. G2-G4
ARRA Grant Recipients/ Total $185M DOE Initiative	Beginning 2009	PP. G5-G9
DOE International Energy Storage Database	Ongoing	P. G9
Hawaii Battery Projects	Beginning 2009	PP. G10-G15

Road Maps

Suggested Guide for Utility and Co-op Engineers/System Planners

What are the relevant use cases for electricity storage?

Chapter 1 identifies storage services and functional uses including storage for renewable integration and provides ranges and minimum requirements for storage systems with illustrative examples. The use cases and applications span generation, transmission and distribution (T&D) as well as customer-side applications.

What are the technology options and how can use cases of interest be assessed?

Chapter 2 describes current storage technologies and their high-level performance characteristics, maturity, and costs in dollars per kilowatt ($/kW) and dollars per kilowatt hour ($/kWh).

Chapter 4 identifies various technology-assessment tools from preliminary screening to more detailed analysis. Selected tools are described in Appendix A.

What are the costs and important procurement and installation issues?

Chapter 4 presents two different system procurement/ownership options for investor-owned utilities (IOUs) and co-ops. It addresses practical safety, interconnection, warranty, and codes issues to guide successful project completion.

Appendix B gives detailed system and component cost information organized by storage technology. These data were obtained from system vendors for the various technologies currently in use for stationary applications and were used to derive the capital costs in Chapter 2.

Appendix C provides sample Requests for Information (RFIs) and Requests for Proposals (RFPs) that can be modified to suit specific needs and serve as guidelines for system procurement processes.

Appendix D illustrates interconnection configurations for selected storage systems and gives representative interconnection equipment costs. These configurations can be changed to meet more specific site needs as necessary.

Appendix C contains a sample specification for cyber security guidance specific to Li-ion battery systems that can serve as a guideline for other storage technology systems.

How have public utility commissions (PUCs) treated storage and what are the regulatory drivers for storage?

Appendix E provides a comprehensive review PUC cases where storage was included and their outcomes.

Chapter 4 summarizes enacted and pending Federal Energy Regulatory Commission (FERC) and State regulatory initiatives that promote storage.

Which trade associations are promoting storage and what are the venues for networking in this community?

Chapter 4 identifies those industry groups and not-for-profit conferences that provide networking opportunities with system vendors, technology developers, and other utilities that use or are considering storage, as well as a window into Federal and State programs that promote storage deployment.

Suggested Guide for System Vendors and Investors

How do utilities and co-ops purchase electricity storage systems?

Chapter 4 presents two different ownership options for electricity storage systems and provides a high-level discussion of safety, interconnection, warranty, and codes that are important from the customer perspective.

Appendix C shows sample RFI and RFP documents that are representative of the terms and conditions that utilities and co-ops will likely seek in the procurement process

Which industry trade groups promote electricity storage?

Chapter 4 identifies those industry groups that actively promote electricity storage and not-for-profit conferences that provide networking opportunities with a wide spectrum of the storage community.

What are the policy and regulatory drivers that impact electricity storage?

Appendix E provides a comprehensive review of past PUC cases that included electricity storage and their outcomes.

Chapter 4 lists enacted and pending FERC and State regulatory initiatives that promote electricity storage.

What are the relevant codes, interconnection, and safety issues?

Chapter 4 discusses safety, interconnection, communication, and warranty issues that are important to prospective customers in the utility sector.

Where can full systems be tested and what are the test standards/protocols?

Appendix F identifies several test facilities and capabilities which can test fully configured systems and discusses the test protocols and standards that are being formulated to govern standardized performance testing of storage systems.

Suggested Guide for Regulators and Policy Makers What are the services and functional uses of electricity storage?

Chapter 1 describes various services and functional uses of electricity storage in the grid with illustrative charts, including the use of electricity storage to support renewable resource integration.

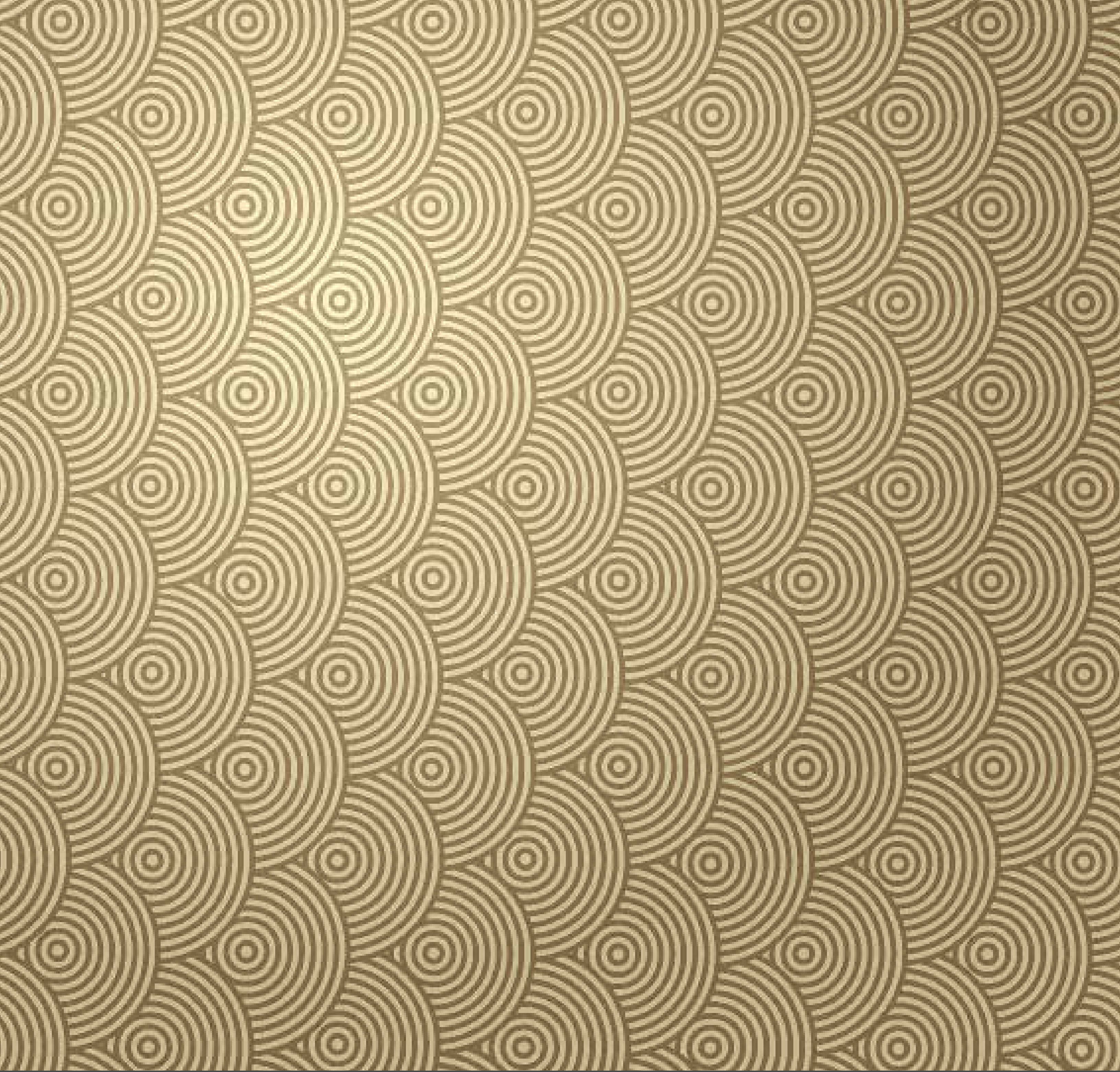
What are the current electricity storage technologies?

Chapter 2 describes current electricity storage technologies, their high-level performance characteristics, and their maturities. Additional cost detail is provided in

Appendix B and Appendix D.

How has storage been addressed by other PUCs?

Appendix E presents a summary of regulatory cases and the outcomes in several State PUC filings that address electricity storage.



Top elevation of compressed springs

15

2015 ESHB Updates

- Thermal Energy Storage Insights & Results
- Energy Storage System Costs Revisions
- Energy Storage Safety Standards Discussion/Best Practices